Updated Report

Improving the Energy Efficiency of Air Distribution Systems in New California Homes

Report for
California Institute for Energy Efficiency (CIEE)

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UPDATE OF ORIGINAL REPORT

The original report for this project was released in 1996; since then the two most critical recommendations from the project have been adopted by the building industry and their regulators. The prevalent home energy rating system (HERS), CHEERS (California Home Energy Efficiency Rating System) now includes duct leakage as part of their rating, and the California Energy Commission (CEC) has included a credit in the California Residential Energy Efficiency Standards ("Title 24") for builders who chose to install tight ducts and test their HVAC systems to verify that they pass (the HVAC system leakage at 25 Pascals must be less than 6% of the system fan flow). The original CIEE project was instrumental in initiating these changes.

There was a need to update the original procedures to reflect the changes in the industry and to be consistent with the HERS and Title 24 requirements. Those are the purposes of this revision to the original report, which follows in its original state.

Updated Procedures for HVAC System Design and Installation

The CIEE HVAC procedures were developed to provide information on design, materials, fabrication, installation, and testing that builders and subcontractors could use to produce improved installations. Since their development in 1995 there have been several changes in the industry that necessitated updating these procedures. The most important of these changes were results of an Lawrence Berkeley National Laboratory (LBNL) study on the longevity of different closure systems[1], and the adoption of credit in the California Residential Energy Efficiency Standards for installation of tight ducts (ducts that leak less than 6% of fan flow). The procedures in Appendix A have been updated to reflect these changes.

The study of closure materials at LBNL demonstrated that normal duct tape (i.e., cloth-backed rubber-adhesive tape), failed rapidly under rapid-cycled heating and cooling conditions. For this reason these tapes are not permitted in the revised procedures nor for duct systems installed to meet the Title 24 tight duct standard.

The other large change in the procedures was changing the criterion for tight ducts from a ratio of leakage to floor area to a ratio of leakage to fan flow. Leakage is determined by pressurizing the system to 25 Pascals (Pa) and measuring the CFM flow to maintain this pressure. The resulting CFM_{25} is then divided by the system fan flow to determine total leakage. The leakage in a finished home must be less than 6% of fan flow to be considered tight. Fan flow can either be determined by direct measurement or by substituting measured return air flow.

There have been no new analyses of costs, cost-effectiveness, or benefits of tight duct systems. The authors believe that the original results still stand. However, it is likely that the implementation of tight ducts in the marketplace due to the changes in Title 24 regulations and other efficiency programs will reduce the costs of installing improved systems.

[1] Home Energy Magazine: 15 #4, July/August, 1998

Implementation of the Recommendations from the Original Report

There were three main recommendations in the original report to get builders to improve the efficiencies of their duct systems:

- Change HERS to include energy savings from reduced duct leakage
- Provide a credit in Title 24 for reduced duct leakage
- Provide motivation to builders through energy efficiency mortgages (EEMs)

For the longer term, there were additional issues to address:

- Provide for increased efficiency from: increased duct insulation, decreased duct surface area, placing ducts in conditioned space, decreased attic temperature due to an attic radiant barrier.

The home energy rating system with the widest market distribution in California is CHEERS. They have changed their rating system in a manner consistent with the recommendations of the original CIEE report. They have reduced the efficiency of the HVAC system in the reference house to reflect that of the current market and they provide for credit in the as-built house reflecting the efficiency improvement specified in the original CIEE report. Ratings are being done in California for homes with tight ducts using the new CHEERS system.

The CEC has adopted Title 24 Standards that will go into effect in July 1999 ("'98 Standards") that provide credit for tight ducts. The CEC approach has been more sophisticated than recommended in the CIEE report and includes all of the issues that the CIEE report listed as longer-term issues. The '98 Standards use a modified version of the ASHRAE 92P model to predict duct efficiency. For the standard-case code-house, the '98 Standards assume duct leakage of 22% from R-4.2 ducts located in the attic. These standards provide efficiency improvements for tight ducts (criterion leakage is less than 6% of fan flow), increased duct insulation, ducts in conditioned space, and attic radiant barrier. Thus, the CEC has not only followed the recommendation that credit be provided for tight ducts, they have also included credits for other HVAC system improvements, which was anticipated to take much longer.

The CEC is likely to initiate a rulemaking process for the technical requirements for HERS that would be approved for use in California. It is likely that the HERS technical requirements regarding HVAC systems will follow the changes employed in the '98 Standards. This would implement all of the recommendations of the initial CIEE report and standardize HERS credits for improved HVAC systems in California.

Builders were anticipated to use HERS to help sell improved homes financed by EEMs. Less progress has occurred in the EEM market. Freddie Mac has published rules that will allow builders to use HERS to document improved efficiency of their homes and use the energy savings in the rating to offset an equal amount of consumer debt. While this is exactly what the builders need to use the EEMs to finance improvements, most lenders and their underwriters are unaware of these rules.

Another goal that was not specified in the original report was a wide distribution and application of the installation procedures. This has also occurred. The three main distribution sources have been:

- Building Industry Institute (BII) Builder Energy Codes Training Program
- BII web page
- ConSol's ComfortWise[SM] program (see future directions).

BII provides an energy codes / quality construction training program to production home builders. The training covers the requirements for Title 24 as well as additional construction issues that will help improve the energy-related quality and comfort of the home. The HVAC installation procedures have been incorporated into the training since 1996. The builders are instructed to follow the procedures and to incorporate them directly into the HVAC contract scope-of-work.

The procedures are also available on the World Wide Web via the BII web site.

Future Directions

There is an energy efficiency program that is designed to encourage new home builders to improve the efficiency of their duct systems, to document the improvement using a home energy rating (specifically a CHEERS rating), and to use EEMs to encourage builders to use the program. This program, ComfortWise, encourages builders to build ENERGY STAR® homes, and tight ducts is a mandatory requirement. The HVAC installation procedures are provided to participating builders to follow in the installation of the tight ducts.

ComfortWise is sponsored by two California utilities, Southern California Edison and San Diego Gas and Electric, as their new construction energy efficiency programs. The total market penetration goal of these two programs is 5,500 homes committed to ComfortWise in 1999. This program, if successful, should demonstrate the value of HERS and tight ducts to the building industry, at least in southern California. Presumably as ComfortWise develops market share, other competing programs will arise. They should also require home energy ratings, and will hopefully require tight ducts and use the CIEE HVAC installation procedures.

[SM] ConSol, Inc., 1997, 1998, 1999
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ORIGINAL REPORT

EXECUTIVE SUMMARY

Procedures for improved design, fabrication, installation, and testing of HVAC systems for new homes were developed under this project. Draft procedures were developed based upon the findings of a review of existing programs that are provided by utilities and others for improved residential duct systems, in addition to discussions with other individuals active in this field. The draft procedures were distributed to production builders in California and their HVAC subcontractors for their review, comments, and estimates of differential costs to implement these procedures. A goal was to develop procedures that would be cost-effective, acceptable to California production builders and their subcontractors, and that would produce significant energy savings. The final version of the procedures, provided in Attachment A, are the result of this process.

This report discusses the potential costs, energy savings, and other benefits of improved residential HVAC systems. The costs were determined through the discussions with builders and HVAC subcontractors. The benefits were estimated through a review of other field studies, discussions with other individuals doing relevant research, and computer simulations of different field situations. A matrix summarizing the potential costs and benefits, separated into different improvement actions (duct sealing, system design, and duct layout), is provided in Section 1. An important finding is that there are immediate heating and cooling energy savings of 12% or more obtainable from duct sealing at an incremental cost of approximately $250 per home (assuming 100% testing). Over the longer term, this incremental cost can decrease to zero due to improved techniques and competition. With the addition of improved system design (such as those including ACCA Manual J and D calculations) and airflow verification, overall savings can be increased by an additional 8% for cooling with little additional cost to production builders (i.e., builders whose costs are spread over multiple houses) in the short term, and potential cost savings in the longer term.

In developing these procedures, it became evident that current practice for sizing ducts and HVAC systems does not properly account for duct leakage and some other duct losses, making it difficult to properly size systems that have minimal leakage. Therefore, this project included a review of the Air Conditioning Contractors of America (ACCA) methods and procedures for design and sizing ducts and systems. Suggested modifications to these methods and procedures are provided in Section 2 of this report and are being actively pursued with ACCA.

Following development of these procedures, an implementation strategy was devised. The goals for this strategy are to provide practical, self-supporting means for the residential new construction industry to adopt and utilize these procedures to produce improved HVAC systems, without any third-party financial incentives. The proposed strategy involves first creating market value for builders using energy efficient mortgages and home energy ratings, which will result in market differentiation between homes with improved HVAC installations, and those with current-style HVAC installations. Second, the strategy proposes to provide credit in Title 24 for improved HVAC systems, and lastly, once there is significant market penetration of improved

HVAC systems, require them as part of the energy codes. That strategy is detailed in Section 5 of this report.

SECTION 1: IMPROVED DESIGN, SPECIFICATION AND INSTALLATION PROCEDURES

This project began with a survey of on-going residential duct programs to determine the state-of-the-art. From this information, a draft set of procedures was synthesized for California new construction. The original work statement for this project identified thirteen sources for information regarding improved design, specification and installation procedures. Of these, nine provided valuable information that was used in the development of the final draft procedures. Additional sources were identified during the survey process, and a total of fifteen contacts were made that provided valuable information that influenced development of the draft procedures (please see acknowledgments).

A factor that limited use of program information from other states was that most of the information uncovered from on-going residential programs was based on retrofit improvements to duct systems. This study was performed exclusively for new construction and focused on California construction techniques, which are primarily flexduct systems installed in the attic.

An important consideration to the installation procedures was whether they should be prescriptive or performance-based. Purely prescriptive programs, such as in Florida (State of Florida, 1993), have been developed that prescribe every detail of material and construction of the duct system. In addition, purely performance programs, such as in the Pacific Northwest (BPA, 1995), have been developed in which ducts may be installed however desired by the contractor, but they must be pressure-tested and proved not to leak more than a criterion amount of air.

The choice was made to make California procedures both prescriptive and performance based. The reasoning was that, while performance testing is thought to be required to ensure proper function, some materials need to be prescribed to ensure longevity of the tested performance. For instance, it is quite possible to install a duct system using low-quality duct tape that will perform very well initially, passing reasonable performance requirements, but that will degrade within a few years, resulting in considerable leakage. It is also very possible to use all of the best prescribed materials, but install the system so that it is not easy to detect that there are leaks. Therefore, prescriptive requirements for materials and performance criteria were both determined to be necessary for a long-lasting, quality duct system.

Two California public utilities had DSM programs for tight ducts – Pacific Gas & Electric and Southern California Gas; both were quite popular with builders, both had both prescriptive and performance elements, and both resulted in improved duct systems. These were used as the core of the proposed procedures, enhanced by elements obtained through the nationwide telephone survey (including reports gained through the survey). The enhancements include requirements for loads calculations, duct layout, duct sizing, equipment sizing, and increased testing requirements (i.e., system leakage, pressure, and airflow).

The procedures are written with a one-page summary of all requirements. That is followed by six pages of detailed information on materials requirements, suggested design, fabrication and installation procedures, and required tests and performance criteria, as well as reference sources for additional information. The procedures suggest room-by-room load calculations using Air Conditioning Contractors of America (ACCA) Manual J, a determination of detailed duct layout and sizing using ACCA Manual D, system sizing using ACCA Manual S calculations, installation using UL 181 approved materials and specified connection techniques, and tests for proper air conditioner size and charge, maximum duct leakage, proper plenum static pressures, and proper air flows. The one-page summary and detailed procedures are provided in Attachment A.

When the procedures are followed, there are two principal, separable actions that result in energy savings, and that have identifiable costs. These actions are 1) Duct sealing, and 2) System design and layout. Industry experience has clearly shown that prescriptive installation procedures alone will not consistently produce HVAC systems that are properly sealed, and that produce proper air flows and distribution. Some testing is required to ensure that the HVAC system is properly designed and installed. The energy savings estimated for each action assumes that sufficient testing is performed to ensure that the HVAC system is performing according to the recommended criteria.

The following matrix has been developed to summarize the potential energy savings and estimated costs and/or savings for each element from the three different issues addressed by the suggested procedures. The cost is per home for a production builder, and assumes volume purchasing discounts as well as amortization of design costs across 25 homes. Negative costs are cost savings.

Actions, Energy Savings, and Costs of Improvements to Residential New Construction Duct Systems

DUCT SEALING

Impact	Energy Savings	Cost (production builder $)
Decreased leakage	Approximately 12% heating and cooling energy savings	$214 materials and labor plus $131 to $163 testing; Estimate $100 to $150 for both with LBNL-aerosol sealing
Increase equipment efficiency by downsizing to keep equipment capacity constant	Approximately 3%	Possible small savings from small downsize of system
Improved system capacity from decreased leakage; same amount as total increase in energy efficiency, approximately 15%	None	-$100 (savings); Potential 1/2 ton downsize
Reduced duct diameter due to equipment downsize; Probably one size decrease; Maybe none if ducts are currently too small	Insufficient data to estimate savings	-$50 (Possible savings if ducts can be substantially downsized)
Two-speed equipment improvements (especially heat pumps)	Estimate 1.7 times single speed savings (20% savings rather than 12%)	None -- do not downsize equip, allow to run more at low speed
Uniform heating and cooling may provide savings through improved thermostat behavior	Insufficient data to estimate; probably less than 10%	None
Range of impacts[a]		
Best estimate (short term)[b]	12% to 30%	$377 to -$50 (savings)
Best estimate (long term)[c]	12%	$250
	20% to 25%	$0

System Design (Manual J and Manual D calculations)

Impact	Energy Savings	Cost (production builder $)
Increase system efficiency due to proper air flow	6% - 10% cooling savings on orifice systems for 10% to 20% increase in coil air flow; No substantial savings for TXV systems	$10 ($87 average cost of Manual J and Manual D calculations spread over 25 homes, plus intermittent field tests of flows ($50 every 8 homes or $25 every 4 homes))
Potential 10% capacity increase	None	-$60 (savings); average 0.3 ton decrease
Reduced duct diameter due to equipment downsizing -- produces improved system capacity (note: ducts may be too small now and there may be a resultant *increase* in size)	Insufficient data to estimate	±$; Unknown whether ducts and systems are currently too large or too small
Uniform heating and cooling; May provide savings through improved thermostat behavior; Unknown	Insufficient data to estimate; probably less than 10%	None
Range of impacts[a]	0% to 10% of cooling	$10 to -$50 (savings)
Best estimate (short term)[b]	4% of cooling	$10
Best estimate (long term)[c]	8% of cooling	-$30 (savings)

[a] Survey and estimate results
[b] Authors' best near-term estimate (some competition)
[c] Procedures part of common practice

SECTION 2: SUMMARY OF PROBLEMS WITH ACCEPTED-PRACTICE DESIGN METHODS

The most comprehensive industry-standard practices for load calculation, duct and system sizing, and system selection are available from the Air Conditioning Contractors of America (ACCA) in their Manual J (loads calculation), Manual D (duct sizing), and Manual S (system selection) publications. The use of these manuals was therefore included in the quality installation protocols developed by this project. Unfortunately, there are simplifying assumptions in these ACCA manuals that can result in incorrect loads, and non-optimal duct and system sizing.

The major concerns regarding Manual J are its assumptions that:

1. there is no duct leakage, and
2. the load due to duct conduction is independent of the length and design of the ducts.

The implication of the first assumption is that the actual load associated with duct losses is, in general, significantly higher than that assumed by Manual J. The second assumption implies that even if the average conduction losses in the duct-loss multipliers in Manual J are correct, the calculated room-by-room loads are incorrect due to non-uniform conduction losses. These two incorrect assumptions can lead to incorrect calculation of loads, and non-uniform heating and cooling. There are other assumptions within the Manual J method that are under control of the user which can be used to bring the calculated loads back into the correct range. These assumptions and some of the implications of their use are discussed in detail in Attachment B. Attachment B also includes a two-stage strategy for improving the quality of HVAC design in California. The two steps are:

1. modify ACCA Manual-J duct loss/gain multipliers to account for the non-uniformity of duct losses and instruct users in its correct use, and
2. incorporate an overall duct loss calculation procedure that determines duct losses based on actual duct lengths and velocities; this requires coordination of Manual J, duct layout, and Manual D calculations.

Attachment B also suggests how these strategies might be implemented through existing ASHRAE committees and standards.

SECTION 3: POTENTIAL IMPACTS ON THE BUILDING INDUSTRY AND ON THEIR CONSTRUCTION COSTS

Industry Survey using Proposed Procedures

Draft procedures were sent to 20 production builders and 25 HVAC subcontractors for review and comment. The reviewers were asked to comment on the practicality of the proposed procedures, to indicate what procedures they already followed, what problems they might encounter with the proposed procedures, and any additional costs or cost-savings that might be incurred due to the procedures.

Responses were obtained from 12 builders and 19 HVAC subcontractors. Their responses were used to make minor changes to the suggested procedures, to analyze costs of the procedures, and to aid in development of the implementation strategy.

Summary of Important Comments

This subsection is a summary of comments made by respondents to indicate their current view of residential HVAC practices in California, and some of the difficulties that the builders and HVAC contractors foresee in improving the HVAC systems.

It was generally held by the survey respondents that the procedures were a good idea, but that their implementation would produce additional costs and that the market would not, by itself, support these additional costs. There was also general consensus that the industry could benefit from improved regulation, but concern was expressed about any new regulations, how they might be structured, and most importantly, how they would be enforced. Many indicated that if current Uniform Mechanical Code (UMC) regulations were enforced that most duct leakage problems would be solved.

Those that had experience with high-performance (i.e., sealed) duct programs supported by utility incentives liked them. Through those programs, HVAC subs were provided with sufficient funds to install a better system and still make money. The builders also felt that they were receiving better ducts. One Southern California HVAC manufacturer said that only ¼ of the HVAC subs were able to work with the utility program requirements because of their limited experience and training. Most cost data for installing sealed ducts that was provided by builders and subcontractors came from experience in the utility programs. This cost data is therefore quite accurate in that it is based on actual experience in the installation of tight duct systems that were tested and passed program criteria.

There was general consensus that the California building industry typically does not employ ACCA or ASHRAE sizing calculations for the duct system. Rather, they are based on experience and "rules of thumb." This leaves an unquantified potential for implementation problems associated with requirements for detailed load calculations, duct layouts, and duct and equipment sizing and selection. A few individuals raised the issue as to whether such a requirement would increase their paperwork, which will add costs.

The potential impacts of testing were difficult to quantify from this survey. Because testing is currently not done on a regular basis, neither builders nor HVAC subcontractors (with a few exceptions) know what tolerances are reasonable, and what the cost would be to perform the testing. In addition, there were significant concerns voiced regarding the logistics of performing testing, mostly from the builders, and what they should be expected to do if the system fails testing, especially regarding air flow requirements. This concern came from both builders and subcontractors. In general, although most understood and appreciated the necessity of some testing, and of establishing tolerances for passing, they warned against too strenuous requirements that would not be cost effective.

Reviewers of the procedures were divided on what values should be used for supply and return air flow tolerances, most contending that as proposed they are not practical. For this reason, the tolerances for supply and return air flows, in section 3b of the testing requirements should be treated as place-holders until there are more test data that can be used to determine reasonable values. This could be done in a pilot program.

Increases in Construction Costs

The California residential building industry has limited experience with large portions of the suggested procedures; therefore, only a limited number of respondents were willing to estimate the incremental costs that would result from implementation of the suggested procedures. When costs were estimated, respondents were questioned to differentiate costs due to requirements for design, materials and labor for fabrication and installation, and testing of the systems. All those responding with cost information had participated in a utility tight-duct program and had direct experience with the costs for those programs. The utility programs also provided most of the respondents with some experience in the costs of testing, although it was more limited. When costs were estimated from utility incentive program experience, the respondents provided their best estimates of actual cost, not incentive values; both builders and HVAC subcontractors who provided this information were very open in their discussion of costs versus incentives. A summary of cost estimates from the survey is provided in Table 1.

Some respondents were only able to provide some of the desired cost information. For instance, some respondents (both builders and HVAC subcontractors) had no experience with ACCA procedures and therefore could not estimate the time and cost required to perform them. In such cases, a high estimate (for a production builder) of the cost -- deemed a placeholder value -- is included in Table 1. These placeholder values were based on this researcher's recent experience outside of this survey of higher costs that are paid by builders for these calculations. High-cost placeholder values were used to minimize the likelihood that the resultant average might underestimate the cost impact to the industry, which could otherwise lead to later invalidation of the findings and resultant recommendations. Table 1 provides average costs determined both with and without the placeholder values.

Cost estimates were also obtained through a direct bid process. Several builders were asked to submit plans to their HVAC subcontractor(s) to get a bid for a typical installation and a second bid on the same home using the suggested improved procedures. One HVAC subcontractor (H6) returned information for two builders. His bids that employed the recommended installation procedures were $167 more than without; this corresponds well to the survey estimate of $150 incremental cost for this HVAC subcontractor. This subcontractor currently includes some of the recommended procedures in his normal work and therefore did not add any incremental cost for these actions. For instance, he performs ACCA Manual J and D calculations on all homes for load calculations and duct sizing, and develops a duct layout on the plans so that he can prefabricate the duct system in his factory before shipment to the job site. Therefore, there was no additional cost for this HVAC subcontractor due to the requirement for these calculations under the proposed procedures.

TABLE 1
COSTS OF IMPROVED SYSTEMS

Participant	Design	Fab/Installation materials	labor	Leakage Testing	To tal 25/design, test all	1/design, test all
H1	250	250	incl	125	385	625
H2	100	50	325	250	629	725
H3	250	100	220	incl	330	570
H4	150	150	75	150	381	525
H5	82.5	50	incl	60	113	193
H6	incl	150	incl	200	350	350
H7	250	45	150	100	305	545
H8	150	30	60	160	256	400
B1	250	300	incl	250	560	800
B2	250	100	incl	250	360	600
B3	40	300	incl	250	552	590
Average with placeholders	161	139	75	163	384	538
Average without placeholders	87	139	75	131	348	432

notes: [shaded] means high placeholder because no value wasprovided
participant prefix H denotes HVAC subs and B denotes builders

He also rejected certain recommendations and therefore omitted them from his bid. For instance, he oversizes the total system capacity by 20% (10% if it is a multi-zoned system) over the total load as a safety margin. He uses manufacturer and UL approved factory connections employing a clear duct tape that he argues seals well and has good longevity. He argues that there is no immediate method to obtain any cost savings due to downsizing that could result from sealed duct systems. He also has his own, manufacturer approved, method for sizing returns that he believes is adequate and provides the design static pressure. No data from systematic tests were provided or requested to substantiate these claims.

It is likely that with experience, builders and their HVAC subcontractors will find methods to design, fabricate, install, and test their duct systems that are more cost-effective than the experience upon which they base their current predictions. It is anticipated that once there is recognized market value for improved HVAC systems, that due to experience and competition, the combined cost for the fabrication, installation, and testing will be closer to $250 for the recommended procedures than the average $346 - $383 estimated from the survey results. In addition, as new techniques become available, these costs will be even lower. For instance, the authors estimate that the LBNL aerosol sealing technique, which combines sealing and pressure testing in a single effort, will cost $100 to $150 for production homes (Modera et al. 1996).

Decreases in Construction Costs

During the survey and bidding processes, respondents, especially HVAC subcontractors, were asked to consider and estimate potential cost savings that could result from downsizing equipment and ducts. None saw any immediate potential for such savings. This is because they either do not currently use sizing procedures such as the ACCA Manual J, D, and S procedures and have no experience or basis to estimate a savings, or because they do use these methods and assume (correctly, if all other assumptions are held constant -- see Section 2 and Attachment B) that they will get the same sizing results from their calculations after adoption of the proposed fabrication and installation procedures as they do now with their current fabrication and installation procedures.

Nevertheless, it should be possible for HVAC systems to be downsized from their current values due to duct sealing. Field studies have demonstrated increases in system capacity associated with duct-system retrofits (Modera and Jump, 1995). Downsizing could be realized in practice through improved ACCA calculation methods, which would require the more widespread use of these standard calculation methods and procedures for loads and sizing, and standardization of the calculation variables, as discussed in Section 2 and Attachment B. Downsizing could also result from industry experience with sealed ducts. Builders and HVAC subcontractors should come to understand that if additional cooling and heating capacity is provided because the ducts are sealed, then a similar amount of capacity can be removed from the system requirements. This will require industry education and experience with sealed HVAC systems, but may be the quickest route to system downsizing.

If downsizing due to tight duct systems occurs, for a 3 to 3½ ton air conditioning system, which is typical in California new construction, a 15% or approximately ½ ton decrease in capacity should be possible, resulting in a cost savings of approximately $100 for a minimum efficiency, 10 SEER air conditioner (this is the approximate savings to a production builder – savings to custom builders would be greater). Savings for high-efficiency systems will be greater. Savings may also be available for downsizing the ducts; however, it is not currently known whether California duct systems are typically over, under, or correctly sized, so no savings can immediately be predicted.

SECTION 4: VALUE OF IMPROVED AIR DISTRIBUTION SYSTEMS TO THE BUILDING INDUSTRY

Value Perceived by the Industry

There was general agreement among survey participants that the building industry needs to improve the duct systems. The main value was perceived as improved quality of the homes. There was no consensus that these improved ducts would save builder costs by decreasing consumer call-backs, allowing for down-sizing, or decreasing liability exposure. However, it was the consensus of an industry working group, including the Technical Director of CBIA and the Chairman of the CBIA Energy Committee, that there will be real but currently not quantifiable (due to lack of data) savings to builders due to decreased call-backs, equipment downsizing, and decreased litigation costs resulting from improper heating and cooling. The savings from decreased call-backs will occur immediately, but are not currently quantifiable because there are no comprehensive data currently available regarding the frequency of HVAC call-backs -- for either the HVAC subcontractor or the builder. The potential savings from equipment downsizing will occur over a longer term as the industry improves its sizing procedures and becomes convinced that with tight ducts equipment can be downsized.

There was general agreement that improved ducts could cost-effectively decrease homeowner energy use, which was good, and which could be used to help market comfortable, energy efficient homes, but that it would not *a priori* help them sell homes.

Energy Savings Potential

To estimate the potential energy savings from tight ducts, building simulations were performed. The losses in a duct system derive from a combination of conduction through the duct walls and leaks at the connections in the air distribution system. Through improvements in connections to decrease leakage, duct efficiency can be improved 12% to 15% if sealing procedures such as those proposed were implemented (Jump et al., 1996; Modera, 1993; Modera and Jump, 1995; CEC, 1995; Proctor and Pernick, 1994).

These energy savings percentages can be understood based on the following. The leakage specification of the leakage flow in cubic feet per minute (cfm) at 50 Pa pressure differential being less than or equal to 0.07 times the house floor area (ft^2) translates to the elimination of approximately 70% of the duct leakage in a typical installation. For example, a 1761 ft^2 house would be allowed to have 123 cfm of leakage at 50 Pa, as compared to an average leakage of 406 cfm at 50 Pa for a typical California house of this size (Modera, 1993). The typical leakage areas correspond to leakage flows on the order of 15% of the fan flow on both the supply and return sides (Jump et al. 1996, Jump and Modera 1994), where the results from Jump were reduced to account for their somewhat larger than average leakage rates. Given these results, the reduction in supply leakage results in a 10.5% increase in energy delivery, and reducing the return leakage results in a 5.25% decrease in energy load (assuming that the energy flux across return leaks is approximately half that across supply leaks, $\Delta T_{return,winter} = 20\text{-}30^oF$ versus $\Delta T_{supply,winter} = 40\text{-}70^oF$, and $\Delta T_{return,summer} = 10\text{-}40^oF$ versus $\Delta T_{supply,summer} = 20^oF$). Adding in the impact of reduced air infiltration while the unit is off (0.7(fraction sealed – from procedures, also CEC, 1995; Modera, 1993)*0.2(fraction of envelope leakage in ducts – CEC, 1995; Modera, 1993)*0.33(fraction of load due to infiltration)*0.85 (fraction of time that equipment is not running)=>4%) yields a total savings of approximately 20%. Some of this savings is not expected to be realized because: 1) some of the leakage is to/from inside the house and new duct installations may be tighter than typical installations, at least in the short term (see CEC 1995), 2) there is some small recovery of losses to buffer zone (attic or crawl space), 3) there will be increased conduction losses if the ducts are sealed without any changes in design or insulation due to reduced flow rate through the HVAC system (see Jump et al. 1996), and 4) some of the savings will be lost due to degradation of equipment efficiency (due to relative oversizing resulting from sealing).

The energy savings from this improvement in distribution system efficiency were estimated using California Residential Energy Efficiency Standards (Title 24) energy use analyses under the typical and improved conditions. A house typical of current new construction practices was modeled using standard Title 24 procedures.

Typical builders in California use the performance approach to Title 24 compliance because it provides them with flexibility to design and build their homes to their own distinctive styles. Title 24 prescriptive packages have glazing limitations and thermal mass requirements that make them impractical for the production builder. Using the performance approach, the builder can "trade" other features for more glass and less thermal mass, for instance. To do so, the builders proposed design is determined, using the Title 24 modeling assumptions, to utilize no more energy for space conditioning and water heating than would have been used had the home been designed using the prescriptive packages. The performance approach was used to determine potential energy savings and to compare these savings to those available from other potential energy conservation features with different costs and benefits.

This energy analysis used a typical two-story house with 1761 square feet of conditioned floor area. For each climate zone, the glazing percentage was set to be the Title 24 package limitation for that climate zone: 16% or 20% glazing (depending upon climate zone), which was equally distributed on each side. The heating, cooling and water heating systems had minimum efficiencies. For each climate zone analyses were performed to investigate the impact of a 12% improvement in duct efficiency due to tighter ducts (using 75% and 84% distribution system efficiencies).

The home was modeled using MICROPAS4 in all sixteen climate zones. The estimated energy savings was calculated from the differences between the typical and improved-case Title 24 heating and cooling budgets for each climate zone. State-wide savings were determined by averaging the savings across climate zones, weighting each climate zone by the new home construction in that climate zone. Each climate zone weighting factor was the percent of the total statewide single-family building from each climate zone in 1993, as published by the Construction Industry Research Board, 1994.

The result was a state-wide average annual savings from duct sealing of 38 Therms and 239 kWh for this typical home. Using current-construction (i.e., not baseline) residential energy costs from PG&E, SCE, SCG, and SDG&E, averaged using the 1990 CEC estimate of utility market shares, these energy savings equate to an annual cost savings of $63 from duct sealing alone.

Energy lost due to ducts leaking is the most easily recaptured. Nonetheless, there are additional, quantifiable savings available through downsizing that can result from the duct sealing, as well as from improved air flow across the air conditioning coil. These savings are estimated to be 3% from equipment downsizing to maintain equipment efficiency (Treidler and Modera 1996, Treidler et. al. 1996), and 8% of the cooling energy for increased air flow across the coil for non-TXV air-conditioners (Rodriguez et al. 1995). This is an additional 10 Therms and 220 kWh or $38 annual savings. There are additional heating-energy savings (particularly for heat pumps) associated with increased air flows, however these are not quantified or included in this report. These savings come at the additional cost of $87 for the duct layout, ACCA Manual J and Manual D calculations plus the cost of flow testing in 12-25% of the homes, which, when amortized over 25 homes, comes to $10 per home.

These savings estimates are all based on Title 24 calculated, climate-zone weighted, average annual budgets of 319 Therms for heating and 1995 kWh for cooling. These values could be optimistic for statewide energy-savings estimates due to the Title 24 use of occupancy schedules that assume that someone is home during the day, its choice of thermostat settings, and fact that it allows cross-over use of heating and cooling in the same day. To determine whether this Title-24-based analysis seriously over or under estimates heating or cooling energy use in this study, a comparison was made to the CEC published typical heating and cooling energy use in their 1990 report on Occupancy Patterns and Energy Consumption in New California Houses. That report provides statewide average energy use (UECs) for California Homes built between 1984 and 1987 of 320 Therms for heating and 1370 kWh for cooling (based upon conditional demand analysis, and which includes a lower air conditioner saturation rate than is found in production housing, therefore underestimating cooling energy use compared to this study). These data are similar to those used as the base for this study, and suggest that the savings estimates from this study are reasonable.

Cost/Benefit Comparisons of Duct Sealing to Other Features

To determine the relative cost-effectiveness of tight ducts to other features, a parametric analysis of 38 other features was performed and a cost-benefit ratio was used to compare tight ducts to the other conservation features. These other features included increased insulation levels, improved windows (both U-values and shading coefficients), shading devices, increased HVAC efficiencies, and water heating equipment efficiencies and features. Each feature was analyzed separately, to determine the energy savings that it would produce independent of other design changes. In addition, incremental costs for each feature were determined from a cost database that ConSol maintains based on on-going discussions with builders, subcontractors, and vendors. To determine energy savings, the home was modeled with none of the improved features (the base-case) for each of three representative climate zones (CZ03 Bay Area, CZ10 Los Angeles, CZ12 Central Valley), and these results were compared to the energy use when the improved feature was included. The resulting energy savings for each feature, as a function of the incremental cost, were compared using the cost-benefit ratio (incremental cost divided by the kBtu/ft^{2}yr savings). For illustration, the feature from each improvement category that had the lowest ratio (low cost, high benefit) from each category of feature is provided in Table 2 for each climate zone. As can be seen in this illustration, duct sealing is two to four times as cost effective as all other permanent features (i.e., not including roller shades), depending upon the severity of the climate zone.

Table 2: Comparative Cost Effectiveness
($ incremental cost / $kBtu/ft^2yr$ energy savings)

	Climate Zone		
Improvement	**3**	**10**	**12**
Duct sealing	*83*	*41*	*34*
Insulation	435	280	521
Window U-values	223	151	162
Window SC	n/a	169	266
Roller Shades	n/a	48	42
A/C SEER	816	263	130
Furnace AFUE	208	101	132
Duct insulation	436	202	177
Water heater EF	185	185	185

Details of this analysis are provided in Attachment C. Detailed information includes the energy savings, incremental cost, and cost/benefit for each of the forty-one features analyzed in all three climate zones.

Duct Sealing Cost-Effectiveness

The portion of the suggested procedures that are the best understood and easiest to implement, and that have the greatest effect on energy use are those that affect duct air leakage. A reasonable method to demonstrate their cost effectiveness is a calculation of simple pay back. Using the annual cost savings of $63 for a 12% savings from tight ducts alone, the average estimated costs from the survey of $214 to fabricate and install the tight ducts and $131 to test the ducts for leaks (total incremental cost $345), the simple pay back for these improved ducts is 5.5 years. The cost estimates from the survey are likely conservative (high), and with experience and competition, the industry will likely find that the marginal cost of improved fabrication, installation, and testing the ducts is closer to $250. If this turns out to be the case, the simple pay back for duct sealing alone falls to 4 years, without any downsizing or additional savings from improved cooling coil efficiency.

If the industry accepts that the HVAC systems can be downsized because the ducts are not losing capacity through leakage, an additional 3% energy savings can be obtained, as well as a cost savings. The air conditioner and air handler downsizing likely from tight ducts is estimated at approximately one-half ton in a typical California home with air conditioning (15% savings from a 3 to 3.5 ton air conditioner), which would produce a cost savings of approximately $100. The combination of sealing and downsizing due to sealing increases the potential energy savings to 15% or $79 annual savings. The associated cost drops to $150 ($250 for sealing minus $100 cost savings from downsizing), producing a simple payback of 1.9 years.

If the experimental aerosol-based sealing technique invented and developed by LBNL proves successful, and our cost estimate of $100 to $150 proves to be accurate, then the simple pay back for the 12% energy savings from duct sealing is 1.6 - 2.4 years, without downsizing or other effects. If this technique is successful, it should reliably produce total system leakage of 50-60 cfm at 50 Pa (or 0.03 times floor area in ft^2), increasing the savings by 24% and decreasing the payback by 20%.

Combined Duct Sealing and System Design Cost-Effectiveness

The survey results clearly indicated that the majority of the California HVAC subcontractors currently do not use procedures such as the ACCA Manual J, D, and S to size ducts and equipment. If the industry can more broadly adopt these procedures, air flow across the air conditioner coil will be improved producing a 6% to 10% increase in energy efficiency. This will be accompanied by a 10% decrease in air conditioner size, producing a $60 cost savings. The energy savings from duct sealing and the resulting downsizing coupled with that from improved air flow across the coil due to improved design and construction, increase the annual savings for the typical house to $101 (15% heating savings, 23% cooling savings). Assuming that the industry has moved to the lower $250 cost for sealing and testing, that the cost of the ACCA calculations is amortized over 25 homes for a cost of $10 per home, and that there is cost savings from downsizing due to sealing ($100, see previous section) and due to improved coil air flow ($60), the total cost is $100 and the simple pay back improves to 1 year. In addition, if the ducts were sealed and tested with the aerosol technique, with downsizing the there is an immediate cost savings.

A different method to view the value of the energy savings is using a present value analysis of the future cost savings, such as a life cycle value (LCV) calculation. The life cycle chosen could range from 15 years (representing a short life for an HVAC system) to 25 years or more (representing the duration of the mortgage). The following table summarizes the Title 24 estimated energy and energy-cost savings resulting from tight ducts, demonstrating the considerable value of the discounted future savings.

Table 3: Cost Savings from Improved Ducts

Duct sealing only (12% heating & cooling savings)

	Therm	kWh	Total	Net Present Value
saved	38	239		($250 cost est.)
annual value	$30	$33	$63	-$187 (first year)
15yr LCV	$358	$409	$768	$518
20yr LCV	$443	$508	$951	$701
25yr LCV	$516	$594	$1,109	$959

Sealing and downsizing due to sealing (15% heating, 15% cooling savings)

	Therm	kWh	Total	Net Present Value
saved	48	299		($150 cost est.)
annual value	$37	$42	$79	-$71 (first year)
15yr LCV	$448	$512	$960	$810
20yr LCV	$555	$635	$1,190	$1,040
25yr LCV	$645	$743	$1,388	$1,238

Table 3: Cost Savings from Improved Ducts (continued)

Sealing and downsizing and improved coil air flow (15% heating, 23% cooling savings)

	Therm	kWh	Total	Net Present Value
saved	48	459		($100 cost est.)
annual value	$37	$64	$101	-$1 (first year)
15yr LCV	$448	$785	$1,233	$1,133
20yr LCV	$555	$973	$1,528	$1,428
25yr LCV	$645	$1,139	$1,784	$1,684

Table 3 notes:

1. The annual value of savings assumes values of $0.14/kWh and $0.78/Therm, which were calculated using 1995 PG&E, SCE, SCG and SDG&E rates averaged using 1990 CEC utility market weightings.
2. The lifecycle value (LCV) assumes the same average values for kWh and Therms and a 3.2% annual inflation and 3.0% real discount rate. If the annual inflation rate is increased to 5.0% and real discount rate increased to 4.0%, the LCVs are extended by about 5 years.

SECTION 5: STRATEGIES FOR IMPLEMENTATION OF SUGGESTED PROCEDURES

There are several methods that could be used to implement the procedures for improved duct systems that were developed under this project. A basic tenent of the recommended strategy is that a simple, energy-code (Title 24) based strategy will not result in rapid market transformation from current practices to the proposed practices. While Title 24 has been very effective in increasing the energy efficiency of California housing, its major successes have been limited to those that are easily and quickly inspected by builders and building officials.

As discussed in Section 3, some of the duct leakage problems that exist today could be resolved by close adherence to the requirements of the UMC. However, these requirements are not easily inspected and discrepancies often go without being inspected and/or they are not noticed. The only certain method to assure proper HVAC system performance is to have the systems tested. Testing could be done by building officials, but it is not likely that they could afford to staff such a requirement, even on a limited basis. Therefore, some alternate method needs to be devised that will result in better designs, use of better materials, improved installations, and testing of the installation. This alternate method needs to both encourage these improved practices, and compensate builders for additional costs that will occur during market transformation.

Such an approach has been successfully employed by two California utilities through demand-side management (DSM) programs which provided incentives that covered the incremental cost of the improvements and testing, and provided marketing support for participants. While this might have been an effective implementation pathway, these programs have been eliminated or severely curtailed and do not provide a likely method for the near future. Thus some alternate strategy that has similar components is required.

Toward this end, a market-driven strategy is recommended that establishes value in the market for improved HVAC systems. It includes code-based elements for inspectable materials and market-based credits for improved design and installation. This strategy combines additions to Title 24 mandatory features for duct-connection materials, changes in Title 24 assumptions to support credit for improved HVAC systems, changes in home energy rating system (HERS) requirements to include diagnostics, and adoption of energy efficiency mortgages (EEMs) to demonstrate value and help finance a market transformation. The steps in implementing this strategy are:

Immediately:
1. Fix HERS reference house duct efficiency at 72%,
2. Adopt HERS testing protocols for duct testing,
3. Permit the HERS proposed house duct efficiency to be increased if prescribed tests are performed and criteria passed: 81% heating and cooling if ducts are adequately sealed, (12% savings from sealing only); 81% heating and 87% cooling if have adequate air flow across the cooling coil (additional 8% cooling savings).
4. Encourage energy efficiency mortgages (EEMs) that will provide market value for improved HVAC systems and cover the incremental cost to improve them.

In the next version of Title 24:
1. Change the default Title 24 duct efficiency to 72%,
2. Add duct-closure material requirements to Mandatory Measures,
3. Add procedures to obtain credit for installation of improved HVAC systems.

Once a criterion residential new construction market penetration has been achieved:
1. Change the default Title 24 duct efficiency to an appropriate figure based on the then current state-of-the-art,
2. Update the Mandatory Measures as appropriate to reflect use of key duct and duct-closure materials.

Each element of this strategy is described and discussed in the following sections.

IMMEDIATE ISSUES:

Changes to California Home Energy Ratings Requirements

Consumers would demand better HVAC systems if they understood how poorly typical ducts currently perform and how much better they could be. One good way to improve the public understanding of duct issues is through home energy ratings that include diagnostic testing of the HVAC system as described in the proposed procedures. Such ratings of both new and existing homes will help educate the public, provided that the ratings contain results of HVAC diagnostics or identify that HVAC improvements would be cost-effective.

California HERS with incorporation of performance diagnostics provides an immediate mechanism for consumers to identify and quantify the quality of the HVAC system. HERS ratings that include duct diagnostics will produce a significantly lower rating for a home with leaky (typical) ducts than for a home with tight ducts. In addition, sealing the ducts should be one of the most cost-effective, and therefore highest priority changes to the home.

The largest HERS organization in California, CHEERS, is currently piloting the voluntary addition of home diagnostics to its ratings. Some raters have been trained in testing procedures that include duct diagnostics. These are valuable to both new and existing homes, and typically should result in duct improvements listed as a cost-effective option. The recurrence of this option, and the industry response that it should evoke, could, over time, drive new home builders to anticipate consumers' requests for tight ducts by incorporating tight ducts into all of their homes.

For California HERS to encourage tight duct systems, the reference house needs to assume typical, leaky ducts. For new construction, our best estimate of the mean efficiency value is approximately 72% (with considerable variation, see CEC, 1995, Jump, et.al., 1996), which can be improved by 12% (to 81% efficient) when sealed to leak a cfm value equal to less than 0.07 times the conditioned floor area (in sq.ft., as specified in the proposed procedures), and an additional 8% for cooling (to 87% efficient) when the currently restricted air flow across the coil is increased to approximately 400 cfm per ton. Our estimated average 72% efficiency value is comparable to the 71% overall efficiency measured in ducts in crawl spaces in the Pacific Northwest (Olson, et.al., 1994). A similar study in California measured delivery efficiency of 64% ±10% for attic duct systems (Jump, et.al., 1996), as compared to 56% delivery efficiency measured in the Pacific Northwest homes with crawl-space duct systems. Delivery efficiency is the ratio between the heating or cooling delivered at the registers to the heating or cooling supplied by the HVAC. It does not include any recovery of lost heat or cool from the buffer zones to which it was lost. These delivery efficiencies compare reasonably well considering both the large variability among measured delivery efficiencies, and that recovery in efficiency due to recovery from the buffer zones is greater for the crawl-space ducts systems as compared to the attic duct systems.

HERS ratings should assume the low efficiency (72%) unless they are tested to leak no more than the criterion amount. Such diagnostic test procedures are outlined in the proposed procedures, and need to be incorporated into California HERS certification protocols and procedures. Coordination is also required between the CEC, CHEERS and other California HERS organizations to ensure that California home energy ratings are quickly capable of rating HVAC systems in homes and that they are consistent in how that is done. There is currently an ASHRAE Standard under development that should provide a long-term defensible basis for the efficiency estimation procedures, including a protocol for dealing with houses that have yet to be built (ASHRAE 1996).

The CEC can also help promulgate this by encouraging or requiring all home energy rating systems operating in California to be able to provide home diagnostics and to integrate the results into suggested upgrades. While it may not be appropriate to require all ratings to have diagnostics (due to the likely increased cost of a diagnostic rating), it would be beneficial to have all raters trained and competent in such diagnostics.

Consumers will need to become more aware of HERS ratings, and know to ask for them. Because they are already aware of other consumer labels, such as on cars and certain appliances, it should not be difficult for them to grasp the importance and information contained in a home energy rating – they just need to know to ask for one. This sort of public awareness could be developed with assistance from the CEC.

Energy Efficiency Mortgages (EEM)

HERS ratings alone will not promulgate improved HVAC systems in new construction because of their initial incremental cost. This cost will discourage builders from utilizing HERS ratings unless the ratings have a demonstrable value. For improved duct systems to be installed in new homes, a mechanism is required to pay the initial costs of materials, installation, and testing. Both of these issues can be resolved quickly through improved EEM products.

HUD recently announced a new EEM lending guideline for new construction. Previously, the only EEM was a 2% stretch in qualifying ratios, which has had no impact on energy efficiency features in new construction because all homes that comply with Title 24 (and the MEC) are eligible, and most lenders are already stretching 2% or more to qualify borrowers for new California homes. The new lending guidelines allow the borrower, after qualifying for the home, to borrow up to an additional $8,000 or 5% of the mortgage amount (whichever is less) to cover the cost of additional energy features that are cost-effective over the life of the loan, without any additional qualification. Duct improvements easily fit within these guidelines, and, as demonstrated in Section 4, improving duct integrity is one of the most cost-effective features available.

To obtain this additional financing, a home energy rating or similar certification is required to estimate the energy and cost savings due to duct sealing, and to certify that the improvement is cost effective. Thus, if the California HERS requirements include the capability for HVAC system diagnostics, it can provide the certification mechanism required for this mortgage. The combination of HERS and EEMs form the basis of a funding mechanism that can help produce consumer pull-through of high efficiency duct systems.

If utilized, these new EEM loans could be used immediately to sell "more home" (one with a superior HVAC system, for instance) to the buyer for no additional monthly cost to the consumer – i.e., the consumer's combined monthly mortgage and utility bills are less than they would be for the non-EEM qualifying home. The CEC could help educate builders that tight ducts are the most cost-effective additional feature to add to their homes and that it will improve the comfort (and possibly sales) of the homes, without changing the listing price of the homes if any incremental construction cost is wrapped into this new EEM, keeping them affordable.

Builders will find that they can add value, comfort, and salability to their homes through improved HVAC systems funded through EEMs. As builders become aware of these mortgages, they will quickly grasp that they can add features to their homes without loosing potential buyers due to increased prices. The buyer need only qualify for the basic home; by using the EEM he or she can still buy the improved home because the cost of the improvement is counterbalanced by the energy-bill savings. The building industry needs to be educated in the use of these mortgages (as has begun under an existing CEC contract), and the industry also needs to appreciate the value and cost-effectiveness of the improved HVAC system as a primary enhancement, as can be demonstrated by a HERS rating with integrated diagnostics.

For this strategy to work, the HVAC subcontractors need to be trained in the proper installation of HVAC systems to achieve improved system performance. This project developed procedures that will result in an improved system cost-effectively. The combination of HVAC subcontractor training in these procedures, linked with the builder motivation through EEMs and quality assurance certification through the HERS with diagnostics, could result in rapid promulgation of improved HVAC systems.

Title 24 Assumptions and Mandatory Measures

At the next opportunity, the Title 24 default assumption for residential new construction duct efficiency should be set equal to the HERS reference house duct efficiency – approximately 72%. This should be done so that Title 24, HERS, and the market are aligned, and to provide the potential for credit to builders who build homes with more energy-efficient duct systems than is current practice. However, as this would allow builders to trade off other energy efficiency features against duct sealing, it is important to assure that the duct improvements have adequate longevity. Thus, any credit for improving duct efficiency must include a requirement with respect to the longevity of the sealing materials. Our recommendation is that this requirement on sealing materials become a mandatory measure (i.e., independent of whether a high-efficiency credit is being taken).

For tight ducts to be acceptably effective, proper materials need to be used at duct connections to provide good longevity. Currently, the most common material used in duct connections is duct tape, usually inexpensive duct tape. While there have not been definitive studies comparing longevity of different types of duct tapes and mastics, there is considerable field evidence that inexpensive cloth duct-tape dries out and within a few years fails, but that mastic lasts as long as the flexduct. There are other duct tapes being used that are claimed to last longer than the common tapes; testing and rating of these tapes for adhesive properties and longevity would be very useful. A first step has come from UL who has drafted a standard for duct tapes (UL 181 B) that will help rate tapes for their adhesive properties. This UL Standard 181 B is proposed in the procedures as a requirement for any tape closures of duct connections, and as such should become a Mandatory Measure within Title 24.

In the longer term, once improved duct systems are relatively common within the marketplace, we recommend moving the required (or standard house) efficiency back up to 81% to 85%, which would reflect the fact that improved duct installations had become common practice (and that the marginal cost should be minimal - see chart on pages 3-4). The question that remains is how to determine when we have transformed the marketplace to this point, or more specifically, when the short-term implementation strategy has become successful.

At the most basic level, this implementation strategy should be considered successful once a criterion market segment has changed their design and installation practices to result in efficient HVAC systems. Some discussion of market saturation that is beyond the scope of this report needs to occur to determine the criterion market saturation. Nonetheless, when significant market saturation occurs, the strategy should be considered successful, and what now needs to be considered as added value should then become a requirement.

By the time significant market penetration has occurred, competition and new methods will have decreased the cost of these higher efficiency HVAC systems. In addition, the industry will have learned how to cost-effectively test and certify that their systems are as efficient as they need to be to qualify for EEMs. At that point, which is likely to occur before two Title 24 code-cycle changes, Title 24 should be changed to require the more efficient HVAC systems that the industry will have embraced. That change in Title 24 should increase the required efficiency to be whatever that significant market segment has achieved (expected to be approximately 85%), it should include a reasonable method to ensure that the ducts are as efficient as specified (some kind of testing), and should update the prescriptive requirements for materials that ensure the longevity of the improved system.

SECTION 6: DISCUSSION AND FUTURE DIRECTIONS

The analysis presented in this report of how to improve the performance of duct systems in California houses has focused on two basic technical issues: 1) reducing duct leakage and 2) using current industry tools to improve designs, including the impacts on equipment sizing and the flows across air conditioner coils. In addition, several shortcomings of those industry tools were uncovered. However, there are a number of other technical and implementation improvements that could and should be pursued as means of improving the quality of residential HVAC installations. Although detailed analyses of these options are beyond the scope of this project, they need to be mentioned and discussed briefly.

Duct-system efficiency is a function of duct leakage, insulation level, duct surface area, duct location, the thermal conditions surrounding the ducts, and the impact of the duct system on equipment efficiency. The protocols developed in this project address the first and the last of these sources of inefficiency. There are additional practical options that could be employed to improve duct efficiency above the current 72% by addressing the other sources of inefficiency.

Increasing duct insulation levels can be considered an alternative or compliment to reducing duct leakage. The typical duct insulation level in California is R-4.2; increased duct insulation levels of R-6 and R-8 are readily available, and R-11 is also available. A recent study by LBNL analyzed the cost effectiveness of increasing duct insulation levels in new construction (Treidler et al. 1996). The most pertinent result from that study was the finding that increasing supply-duct insulation up to R-8 was cost-effective for attic ductwork.

Another way to decrease conduction losses from ductwork is to install the duct system in conditioned spaces. This type of a change can produce a dramatic increase in duct efficiency (resulting in efficiencies above 87%) because any losses are to the conditioned space and are therefore not considered losses. There are however four issues that need to be dealt with in terms of implementing such an option: 1) there needs to be a way to assure that the ducts are truly located in conditioned space (such as the house-pressure duct leakage diagnostic in the CHEERS rating tool and ASHRAE 152P), 2) the change in construction practice is much more significant as compared to sealing ductwork or adding insulation, 3) the current credit for conditioned-space ductwork within the Title 24 regulations effectively requires the use of a condensing furnace (Jump 1995), and 4) there still needs to be some requirement for high-longevity duct sealing, because if leaks remain, then the conditioned air does not end up where it is supposed to go, and leaks hidden behind walls and in between floors are much harder to access. Conditioned-space ductwork without leak sealing and adequate insulation results in a home that does not perform as designed, and is not as comfortable as it should be.

Duct surface area could also be decreased to improve duct efficiency. Field measurements in California houses has shown that actual duct surface area are approximately twice what is assumed in the current Title 24 compliance tool (CEC 1995). Those same field studies showed dramatic variations in duct surface area, the smallest system having a surface area equal to approximately 6% of the house floor area, and the largest system having a surface area of 65% of the house floor area. Surface areas could be systematically reduced by improving the placement of the HVAC system, changing placement of registers, and other design changes. Specifically, as envelopes and windows have improved, the need to install registers under windows on exterior walls may no longer exist. The ability to provide credit for such changes would require some research to determine typical designs, average surface areas, and reasonable metrics to determine credit. Some reasonable method of field inspection and credit should also be developed to ensure that the installation does, in fact, have a decreased surface area and the resultant decreased conductive losses.

Finally, conductive losses can also be decreased by reducing the temperature difference between the conditioned air inside the ducts and their surroundings (typically attic conditions). This could be achieved for cooling through the use of radiant barriers above the attic air space. Recent studies demonstrate considerable decreases in attic temperature with the use of attic radiant barriers, and resultant decreased duct conductive losses (Hageman and Modera, 1996). Reasonable credits would need to be determined for such installations.

Alternative Title-24 Strategies

Lowering the Title 24 default assumption to 72% may not be immediately acceptable to some energy-code stakeholders because it may be seen as giving away energy efficiency that has been believed to be inherent in new construction. However, changing this assumption to reflect reality is what will allow Title 24 to work with other market drivers, such as EEMs to provide value for improved duct systems. The goal of the recommended strategy is to achieve real energy savings from improved HVAC systems; if Title 24 is not adjusted to reflect reality, then it denies providing builders and consumers any real value for the cost of improved HVAC systems.

It might be argued that we now understand that duct systems are not as efficient as previously assumed in Title 24, and that the energy code should simply mandate the increased efficiency by holding the standard house assumption at its current level. The basic problem with this argument is that there is currently no workable mechanism within Title 24 to enforce such a mandate.

Specifically, the only effective way to ensure that the duct system is working efficiently is to test it. Testing will not be done by building officials; they do not have the staff, expertise, or budget. It is also not realistic to assume that testing could be immediately embraced by the building or HVAC industries if they are required to certify duct efficiency. The problem is that there are too few people who are qualified to test duct leakage, and therefore the most likely outcome is that the leakage certification will become meaningless, as most contractors will not know what to do, and there will be no mechanism for training them or policing their performance. An example of the problems associated with mandating duct testing in the short term can be taken from the insulation certificate. Insulation subcontractors are currently required to certify the installed insulation on a form. A recent study of homes found that 100% of the homes were certified to have the correct insulation, but that an independent inspection determined that 70% of the homes had significantly less insulation than was certified (CEC, 1995-2). For the industry to change in the short term, there needs to be a value associated with that change. That value can come from EEMs and HERS ratings. Title 24 could then capitalize on the change at a future date.

An argument can also be made that some intermediate value should be set for Title 24 duct efficiency that is between the current typical efficiency and the current assumed efficiency – as a compromise between mandates and voluntary programs. Such a strategy serves to decrease the value of change to the builder or contractor by reducing the value that can be obtained from HERs ratings for homes with improved ducts for EEMs. For EEMs to be effective in moving the new construction market from its current practices to efficient duct systems, the change needs to be cost-effective. An intermediate duct-efficiency assumption in Title 24, which if adopted should be reflected in the California HERs guidelines, would diminish the value, sending the wrong message to the industry and potentially making such a change not cost-effective. Care need be taken to ensure that HERs assumptions and Title 24 assumptions become aligned and that they provide sufficient value to improved practices so that they are cost-effective.

Another alternative strategy would be to keep the Title 24 standard house at the current level of duct efficiency, or at some intermediate efficiency level, and to allow multiple alternative means for the builder and contractor to achieve the mandated efficiency level. These alternative means are likely to have a one-to-one correspondence with the other technical improvements discussed in this section. This strategy is attractive in many ways, as it would allow the most flexibility for compliance, while sending the right signals with respect to the performance of duct systems. There are however two problems with this strategy: 1) it requires more detailed analyses of each of the alternative compliance routes, and 2) it diminishes the market forces for making duct sealing an integral part of the residential HVAC industry. Nonetheless, we would support this strategy in the longer term (i.e., once duct sealing has reached critical mass), as the proposed ASHRAE Standard 152P should take much of the technical burden for evaluating these alternatives off of the just the state of California.

Draft Evaluation Guidelines

If a program is put in place to implement improved HVAC systems, it will likely need to be evaluated as to its effectiveness. In such an evaluation, there are several issues that need to be addressed. The major issues and the corresponding variables to be measured are:

Issue	Variable
Has duct leakage decreased?	Duct leakage
Are systems sized correctly?	System size
Are ducts sized correctly?	Duct size, air flow
What energy savings have been achieved?	Energy use
What has been the cost to the builder; to the homeowner?	Costs
What is the market penetration of improved HVAC systems?	Market penetration
Has comfort improved?	Consumer surveys

To evaluate program effectiveness, additional research will be required, both to determine the current basis, as well as to track effectiveness. How this is done is obviously highly dependent on the chosen implementation strategy. This discussion of evaluation procedures assumes that the strategy suggested in Section 5 is followed. While there is a considerable amount of data available for some of the required baseline information, other data will need to be collected; all data for evaluation of improvements will require new research. The following table lists the potential sources of information for each of the key variables, both for baseline and improvements, as well as the estimated status of baseline information (other sources could be developed – this list is not intended to be comprehensive; formal research proposals will likely be required to obtain most of this information and to integrate it into a final opinion):

Variable	Sources	Baseline Status
Duct leakage	LBNL, CHEERS, Utilities	Adequate
Sealant longevity	LBNL	Research required
System size	CHEERS	Research required
Duct size	LBNL	Research required
Air flow	LBNL, CHEERS	Research required
Exit air temp	LBNL, CHEERS	Research required
Energy use	CEC, CHEERS, Utilities	Adequate
Costs	LBNL, CEC	Adequate
Market penetration	CHEERS, CBIA	(assumed minimal)

When an evaluation plan is developed, target values for each variable must be developed. Many of these targets are included in the procedures developed in this project, which are discussed in Section 1 and included as Attachment A. For instance, the procedures provide test criteria for duct leakage, coil air flow, supply and return air flows, and system sizing. If these are promulgated as appropriate, then the evaluation need only track whether they are being obtained. Such tracking could be achieved as part of a large research project where all aspects are evaluated by a single contractor, or a smaller project could track information available from the participating groups. For example, CHEERS may be an integral part of the implementation plan, providing duct leakage and airflow testing so that the builder can qualify for the EEMs. If so, CHEERS could provide some of the information required, in this example, the duct leakage values, system size information, air flow results, energy use estimates, and program participation estimates. This would likely involve a research contract with CHEERS (in this example), as well as some oversight group to provide third-party evaluation and integration, but would likely be a more cost-effective method to obtain evaluation information than to have it done entirely by a non-participating external organization.

SECTION 7: CONCLUSION

This study has resulted in a set of buildable, cost-effective procedures for improved design, fabrication, installation and testing of residential HVAC systems that have been reviewed by a number of builders, HVAC subcontractors, as well as staff from the CEC, NRDC, and CBIA. An analysis of the cost of implementing these procedures and the resultant energy savings has shown that, in the short term there will be some cost to the builder, but that it will result in a cost-effective improvement to the consumer. In the longer term, as builders and HVAC subcontractors improve their techniques, the costs can drop to zero, or even provide some savings in construction costs. In addition, as these implementation improvements occur, there are additional savings to the consumer, making this change in construction techniques even more cost-effective to the consumer.

This project has also resulted in the development of an implementation strategy that utilizes existing market vehicles, primarily home energy ratings with integrated duct diagnostics and energy efficiency mortgages, to produce initial market value and acceptance of improved HVAC systems. This would be followed in the next Title 24 code change with alignment of the Title 24 assumptions regarding duct system efficiency with the California HERs assumptions. The authors feel that this change will reinforce the market value of improved duct systems and allow the driving forces of HERs coupled with EEMs to continue. After significant market penetration has been achieved, we suggest that the Title 24 assumptions be raised to a higher efficiency, recognizing that construction practices have changed.

The final conclusion is that this project has also identified a number of alternative or supplementary means for improving the quality, energy efficiency and performance of residential duct systems that should also prove to be cost-effective. However, the analysis required prior to including those options into the proposed implementation plan was beyond the scope of this project. The options identified included: 1) practical encouragement of ductwork in conditioned spaces, 2) added duct insulation, 3) reducing duct surface by means of better layouts and register locations, and 4) reducing attic temperatures with radiant barriers above the ductwork.

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ATTACHMENT A

PROCEDURES FOR HVAC SYSTEM DESIGN AND INSTALLATION

PROCEDURES FOR HVAC SYSTEM DESIGN AND INSTALLATION

The goal for a HVAC system is to provide proper airflow, heating, and cooling to each room. This page sets out key criteria that describe a quality system, and key design and installation considerations that should be met to achieve this goal. The pages following contain more detailed information on design, fabrication, installation, and performance testing.

Criteria for a Quality HVAC System

An HVAC system should:

1. Be properly sized to provide correct air flow, and meet room-by-room calculated heating and cooling loads;
2. Be installed so that the static air pressure drop across the handler is within manufacturer and design specifications;
3. Have sealed supply ductwork that will provide proper airflow;
4. Be installed with a return system sized to provide correct return airflow;
5. Have sealed return ductwork that will provide proper airflow to the fan, and avoid air entering the HVAC system from polluted zones (e.g., fumes from autos and stored chemicals, and attic particulates);
6. Have balanced airflows between supply and return systems to maintain neutral pressure in the home;
7. Minimize duct air temperature gain or loss between the air handler and room registers, and between return registers and the air handler;
8. Be properly charged with refrigerant;
9. Have proper burner operation and proper draft.

Procedures to Design and Install an Air Distribution System

The following steps should be followed in the design and installation of the HVAC system to ensure efficiency and comfort (for details, see Appendix A):

1. Determine room-by-room loads and air-flows using ACCA Manual J calculation procedures (or substantially equivalent);
2. Layout duct system on floor plan, accounting for the direction of joists, roof hips, fire-walls, and other potential obstructions. Determine register locations and types, duct lengths, and connections required to produce layout given construction constraints;
3. Size duct system according to ACCA Manual D calculation procedures (or substantially equivalent);
4. Size HVAC equipment to sensible load using ACCA Manual S procedures (or substantially equivalent);
5. Install equipment and ducts according to design specifications, using installation requirements and procedures from the Uniform Mechanical Code, the Air Diffusion Council, SMACNA, California Residential Energy Efficiency Standards (Title 24), and manufacturers' specifications; Using these procedures and those in Appendix A, the duct system should be substantially air tight;
6. Charge the system appropriately, and verify charge with the evaporator superheat method or subcooling method (or substantially equivalent);
7. Check for proper furnace burner operation and fire-box drafting;
8. Test the system to ensure that it performs properly by determining (1) that the system is properly sized, (2) it does not leak substantially, and has (3) proper room and return air flows, and proper plenum static pressures. (Procedures are detailed in Appendix A.)

APPENDIX A

Recommended Details for an HVAC System: Materials, Fabrication, Design, Installation, and Performance Testing

MINIMUM MATERIALS SPECIFICATIONS

The following are minimum materials specifications recommended to achieve a substantially tight installation that will last:

All Materials

- Shall have a minimum performance temperature ratings per UL181 (ducts), UL181A (closure systems for rigid fiberglass ducts), UL181B (closure systems for flexible ducts) and/or UL 181BM (mastic);
- Shall have a flame spread rating of no more than 25 and a maximum smoke developed rating of 50 (ASTM E 84);

Factory-Fabricated Duct Systems

- All factory-fabricated duct systems shall include UL 181 listed ducts with approved closure systems including collars, connections and splices;
- All pressure-sensitive and heat-activated tapes used in the manufacture of rigid fiberglass ducts shall be UL 181A listed;
- All pressure-sensitive tapes and mastics used in the manufacture of flexible ducts shall be UL 181B (tape) or UL 181BM (mastic) listed.

Field-Fabricated Duct Systems

- Ducts:
  - Factory-made ducts for field-fabricated duct systems shall be UL 181 listed.
- Mastic sealants and mesh:
  - Sealants shall be UL 181BM listed, non-toxic, and water resistant;
  - Sealants for interior applications shall pass ASTM tests C 731 (extrudability after aging) and D 2202 (slump test on vertical surfaces);
  - Sealants and meshes shall be rated for exterior use;
  - Sealants for exterior applications shall pass ASTM tests C 731, C 732 (artificial weathering test), and D 2202.
- Pressure-sensitive tapes:
  - Cloth-backed, rubber-adhesive tapes (typical duct tape) shall not be used even if UL 181B rated;
  - Tape used for flexduct shall be UL 181B listed;
  - Tape used for duct board shall be UL 181A listed and so indicated with a UL 181A mark.
- Drawbands:
  - Shall be either stainless-steel worm-drive hose clamps or uv-resistant nylon duct ties;
  - Shall have a minimum performance temperature rating of 165 degrees Fahrenheit (continuous, per UL 181A-type test) and a minimum tensile strength rating of 50 pounds;
  - Shall be tightened as recommended by the manufacturer with an adjustable tensioning tool.

DESIGN, FABRICATION, AND INSTALLATION

The following are design, fabrication, and installation guidelines that, if carefully followed, will provide a duct installation that is substantially airtight and that will provide proper airflow to each room of the house:

General Issues

- Ducts, plenums, and fittings should be constructed of galvanized metal, duct board, or flexible duct. Building cavities may not be used as a duct or plenum without a sealed duct board or metal liner.
- The air handler box should be airtight;
- Air filters should be easily accessible for replacement, and evaporator coils should be easily accessible for cleaning;
- Ducts should be configured and supported so as to prevent use of excess material, prevent dislocation or damage, and prevent constriction of ducts below their rated diameter;
- Flexible duct bends should not be made across sharp corners or have incidental contact with metal fixtures, pipes, or conduits that can compress or damage the ductwork;
- Flexible ducts should not have bends that exceed 90º unless specified and accounted for in the design;
- Sheet metal collars and sleeves should be beaded to hold drawbands.

DESIGN HVAC SYSTEM

<u>Loads and CFM Calculation</u>

- ACCA Manual J Load Calculation or equivalent required;
- Calculate heat loss and heat gain for each room;
- Total room loads to determine system requirements.

<u>Lay Out Air Distribution System</u>

- Lay out duct system on floor plan and determine register positions and duct paths to optimize room air circulation and minimize actual duct length as well as equivalent lengths of fittings, bends, etc.;
- Duct paths must account for locations and directions of joists, roof hips, fire-walls, and other potential obstructions;
- Duct paths must be planned to avoid sharp turns of flexduct that will kink the duct.

<u>Size Air Distribution System</u>

- ACCA Manual D Duct Design or equivalent required;
- Calculate correct cfm for each room and total for building for both supply and return;
- Size ducts according to Manual J loads, Manual D air flows, and final layout on plans;
- Choose registers to optimize air distribution and duct static pressure;
- Size and locate returns to optimize airflow per ACCA Manual T;
- For return-filter grills, calculate minimum return filter area per ACCA Manual T.

<u>Select System</u>

- ACCA Manual S Residential Equipment Selection or equivalent required;
- From Manual J loads and Manual D cfm, determine appropriate equipment;
- Equipment should be sized to sensible loads;
- Equipment sensible capacity should not be more than 15% larger than the total sensible design load (as specified in Manual S).

FABRICATE AND INSTALL AN AIRTIGHT DUCT SYSTEM

<u>All Duct Types</u>

- All joints and seams of duct systems and their components should be sealed with mastic, mastic and embedded mesh, or pressure-sensitive tape approved for use by the duct manufacturer and meeting UL181 specifications, excluding cloth-backed rubber-adhesive tapes ("approved tape"); cloth-backed rubber-adhesive tapes shall not be used to attach or seal ducts.
- Junctions of collars to distribution boxes and plenums should be sealed with mastic;
- All sealants should be used in strict accordance with manufacturer's installation instructions and within sealants moisture and temperature limitations;
- All tapes used as part of duct system installation should be applied to clean, dry surfaces and sealed with manufacturer's recommended amount of pressure or heat. If oil is present, taped surfaces should be prepared with a cleaner / degreaser prior to application;
- All register boxes should be sealed to the drywall or floor with caulking or mastic.

<u>Flexible Ducts</u>

- Flexible ducts should be joined by a metal sleeve, collar, coupling, or coupling system. At least 2 inches of the beaded sleeve, collar, or coupling must extend into the inner core while allowing a 1 inch attachment area on the sleeve, collar, or coupling for the application of tape;
- The inner core should be mechanically fastened to all fittings, preferably using drawbands installed directly over the inner core and beaded fitting. If beaded sleeves and collars are not used, then the inner core should be fastened to the fitting using #8 screws equally spaced around the diameter of the duct, and installed to capture the wire coil of the inner liner (3 screws for ducts up to 12" diameter, and 5 screws for ducts over 12" diameter);
- The inner core should be sealed to the fitting with mastic or approved tape;
- Tape used for sealing the inner core should be applied with at least 1 inch of tape on the duct lining, 1 inch of tape on the fitting of flange, and wrapped at least three times;
- The outer sleeve (vapor barrier) should be sealed at connections with a drawband, and either mastic or three wraps of approved tape;
- The vapor barrier should be complete. All holes, rips, and seams must be sealed with mastic or approved tape.

<u>Metal Ducts and Plenums</u>

- Metal-to-metal connections should be cleaned and sealed in accordance with manufacturer's specifications;
- Openings greater than 1/16 inch should be sealed with mastic and mesh or approved tape;
- Openings less than 1/16 inch should be sealed with mastic or approved tape;
- Special attention should be paid to collar connections to duct-board and/or sheet metal; seal around the connection with mastic;
- Connections between collars and distribution boxes should be sealed with mastic;
- At least three equally-spaced #8 screws should be used to mechanically fasten round ducts (3 screws for ducts up to 12" diameter, and 5 screws for ducts over 12" diameter);
- Crimp joints should have a contact lap of at least 1½ inches;
- Square or rectangular ducts should be mechanically fastened with at least one screw per side.

<u>Duct Board</u>

- Duct board connections should be sealed with adhesive, mastic, or approved tape in accordance with manufacturer's specifications.

<u>Duct Support</u>

- Supports should be installed per manufacturer's specifications and UMC requirements;
- Supports for flexible ducts should be spaced at no more than 4-foot intervals;
- Flexible ducts should be supported by strapping having a minimum width of 1½ inches at all contact points with the duct;
- Supports should not constrict the inner liner of the duct;
- Flexible ducts should have maximum of ½ inch sag per foot between supports;
- Flexible ducts may rest on ceiling joists or truss supports as long as they lie flat and are supported at no more than 4 foot intervals.

<u>Boots</u>

- After mechanically attaching the register boot to floor, wall, or ceiling, all openings between the boot and floor, wall, or ceiling should be sealed with caulk, mastic, or butyl-adhesive tape.

<u>Seal Air Handler</u>

- Openings greater than 1/16 inch should be sealed with mastic and mesh, or butyl adhesive tape;
- Openings less than 1/16 inch should be sealed with mastic or UL 181A listed tape;
- Unsealed access doors should be sealed with UL 181A listed tape.

CHECK REFRIGERANT CHARGE

- For systems with fixed metering devices use evaporator superheat method:
  - indoor coil airflow must be <u>greater</u> than 350 cfm/ton;
  - refrigerant system evacuation must be complete (all non-condensables must be removed from the system;
  - in hot, dry climates be cautious to be within range of superheat charging chart or use a different method.
- For systems with thermostatic expansion valves (TXV) use the subcooling method.
- Install an access door for field verification of the TXV.

CHECK COMBUSTION PERFORMANCE

- Check each chamber for correct flame;
- Check for proper drafting.

TEST SYSTEM PERFORMANCE

The following are testing requirements and procedures that must be followed to ensure that the HVAC system has been properly installed. The tests are designed to determine whether:

1. *Room-by-room airflows are correct;*
2. *Total supply is as designed;*
3. *Total return = total supply;*
4. *Ducts, plenum, and air handler are tight;*
5. *Static pressure is correct.*

- Test the system to ensure that it performs properly, by (1) verifying HVAC equipment sizes installed are those specified, (2) measuring duct leakage, and measuring (3) supply and return flows and plenum static pressures:
  1. Air conditioner sensible capacity must be no more than 15% greater than the calculated sensible load; fan flow must be greater than 350 cfm/ton; check that the correct size air handler is installed.
  2. Ensure that the duct system does not leak substantially:

   a. A rough system, including both supply and return but without the air handler, must leak less than 4% of specified fan flow (cfm leakage measured with HVAC system pressurized to 25 Pa);
   b. The finished installation, including supply, return, the air handler and finished registers, must leak less than 6% of measured fan flow or of measured return flow (cfm leakage measured with HVAC system pressurized to 25 Pa);
3. Supply and return air flow, and static pressure requirements: Ensure that supply and return flows are correct, and that the static pressure across the fan is correct:
   a. Measure room-by-room air flows to ensure that each register is within 15% of Manual D design air flow, and that the entire supply is within 5% of design;
   b. Measure return airflow to ensure that it is within 5% of the total supply airflow;
   c. Test static pressure drop across the blower to ensure that it is within 0.1 inch water gauge of design and manufacturer specifications.

- Duct leakage can be determined using a pressurization or depressurization technique; for details, California Energy Commission ACM Manual Appendix F, Minneapolis Duct Blaster™ manual, or manuals for other commercially available duct pressurization or depressurization devices;
- Fan flow, supply flow and return flow measurements, see Minneapolis Duct Blaster™ manual (or equivalent); alternatively for supply and return flows, use a calibrated flow hood. Do not use a Pitot tube, or any type of anemometer to determine these airflows;
- Static pressure drop across the fan is measured using static pressure probes in the return plenum and in the supply plenum.

REFERENCES

UMC	1991 Uniform Mechanical Code Sections 1002 - 1005 and Appendix A, Standard No. 10-5.
Air Diffusion Council, Flexible Duct Performance & Installation Standards.	
ACCA	Air Conditioning Contractors of America, 1515 16th St., NW, Washington, DC 20036, (202) 483-9370
ACCA Manual J, Seventh Edition, 1986	
ACCA Manual D, New Edition, 1995	
ACCA Manual S, New Edition, 1995	
ASHRAE	1791 Tullie Circle, N.E., Atlanta, GA 30329, (404)636-8400
ASTM E 84	Test for Surface Burning Characteristics of Building Materials
ASTM C 731	Extrudability After Aging
ASTM C 732	Artificial Weathering Test
ASTM D 2202	Slump Test on Vertical Surfaces
California Energy Commission	1516 9th Street, Sacramento, CA 95814-5512, (800) 772-3300
SMACNA Manual	Installation Standards for Residential Heating and Air Conditioning Systems
UL Standard 181	Standard for Factory-Made Air Ducts and Air Connectors
UL Standard 181A	Standard for Closure Systems for Use with Rigid Air Ducts and Air Connectors
UL Standard 181B	Standard for Closure Systems for Use with Flexible Air Ducts
UL Standard 181BM	Standard for Mastic Materials

ATTACHMENT B

PROBLEMS WITH ACCEPTED PRACTICE SIZING METHODS:

Relationship Between Duct System Performance, ACCA Design Procedures, and Installed-System Quality

Background

The Air Conditioning Contractors of America (ACCA) association publishes four manuals related to residential heating and air conditioning that address many of the issues associated with residential duct systems. ACCA Manual J (Load Calculation for Residential Winter and Summer Air Conditioning, Copyright 1986) is the industry-standard design-load calculation procedure for residences. ACCA Manual S (Residential Equipment Selection, 2/92) provides procedures for choosing residential heating and cooling equipment based on the loads calculated with Manual J. ACCA Manual D (Residential Duct Systems, Copyright 1995, 2nd Printing) provides design procedures for residential duct systems, focusing on how to produce the desired air delivery at each register, as well as discussions of the magnitudes and impacts of duct-system inefficiencies. ACCA Manual T (Air Distribution Basics for Residential and Small Commercial Buildings, UPB592-10M) addresses room air motion issues, focusing on the impacts of register/grille location and diffuser performance.

Treatment of Duct Performance in ACCA Manual J

ACCA Manual J addresses residential duct system performance in three ways: 1) it provides room-by-room loads, which are intended to be used to calculate the energy that needs to be transported by the ducts to each room, 2) it provides a table of duct-loss multipliers that are used to calculate the extra design load associated with conduction losses from the ducts, and 3) it provides a table of recommended levels of duct insulation, and states that “All ducts should have their seams sealed with tape”.

In calculating the energy load impacts of ducts and room-by-room loads, Manual J makes two fundamental assumptions: 1) that there is no duct leakage, and 2) that the load due duct conduction is independent of the length and design of the ducts. The implication of the first assumption is that the actual load associated with duct losses is in general significantly higher than that assumed in Manual J. The second assumption implies that even if the average conduction losses in the duct-loss multipliers are correct, the calculated room-by-room loads are incorrect due to non-uniform conduction losses.

A significant body of research performed over the past five years in California and other states that install ductwork in attics and crawlspaces demonstrates that duct leakage increases space-conditioning energy use by 15-20% on average, even in new construction. This loss needs either to be eliminated, or to be added to the losses associated with conduction gains to obtain correct loads seen by the equipment. Field research has also demonstrated the effective increase in heating and cooling system capacity associated with improving duct performance (Modera and Jump, 1995). Those studies show reduced fractional on-times and increased cycling under the same weather conditions after duct retrofit.

A logical question that arises with respect to these duct leakage losses is why Manual J is not resulting in significantly undersized systems because of the fact that it does not include these duct leakage losses. The reasons for why this is not the case seem to stem principally from the application of Manual J, rather than the manual itself. In general, Manual J leaves quite a bit to the discretion of the user, leaving numerous opportunities for increasing the size of the unit. Some of the common points at which safety margins seem to creep in are:

- The use of the worst house orientation for load calculations,
- The choice of the next size up in the piece of heating/cooling equipment,
- The assumption of 50% RH indoor conditions in most manufacturer's capacity data, which is higher than what is found in much of California, and which results in a lower estimated sensible capacity for a piece of equipment as compared to the sensible capacity the equipment would have at a lower indoor humidity level,
- Using a somewhat lower indoor design temperature,
- Using a higher outdoor design condition, such as 1%, or utility-peak outdoor design temperature rather than the 2.5% values recommended in Manual J.
- Using the next-highest outdoor-temperature rating point, rather than interpolating manufacturer's capacity data.
- The recommendation of 0-15% oversizing of sensible capacity in Manual S.

To be fair, it should also be noted that there are some factors that tend to decrease the size of the equipment chosen with the ACCA procedures, including:

- ARI capacities are normally quoted at 80^{o}F, whereas Manual J requires capacities at 75^{o}F, which will be smaller.

It is very difficult to quantify exactly how much the above trends influence equipment sizing. A contractor survey performed in Florida indicated that there is a large variability in the equipment-sizing practices used by contractors (Home Energy 1995). It is safe to say that there are numerous opportunities for a contractor to increase equipment size within the ACCA procedures so as to maintain the sizing with which they are comfortable. A related study of equipment sizing and ACCA manuals is published in Home Energy magazine (Proctor et al. 1995).

The assumption of constant duct-loss multipliers for all duct sections (or in other words, that duct loads scale with room load, and not with duct design or length) is more of a design-flaw and comfort problem, rather than an energy-use or equipment-sizing problem. Namely, after calculating room-by-room loads including constant duct-loss multipliers, the air flow required for each room is calculated from the loads, the duct system is laid out, and the cross-sectional area of the ductwork is calculated and checked with Manual D based upon the ability of the system to supply the required air flow. This implies that the percentage energy loss from the longest duct run is the same as that from the shortest run. It seems clear that this is not a realistic assumption, however the magnitude of the resulting disparity, based upon field measurements, is striking. Namely, the bedroom closest to the furnace for an R-4 duct system in a Sacramento attic was measured to have 12% of the duct energy lost by conduction on the way to the register. The equivalent losses for the master bedroom at the end of the duct run were more than 40% (Modera and Jump, 1995). The 12% loss is line with the losses that are calculated from the Manual J duct loss multipliers, and the 40% loss clearly indicates that the master bedroom duct is most likely undersized. Sure enough, the homeowner commented on the improvement in master-bedroom conditions after the retrofit. The end result of this disparity is that the entire duct-design process is skewed so as to provide far less than optimal distribution of heating and cooling.

There is another assumption within Manual J that is likely to result in inaccurate estimates of room-by-room loads. Namely, it is assumed that the infiltration load is split between rooms based on the estimated relative external leakage area of that room. The problem with this assumption is that it ignores the fact that a significant fraction of residential air infiltration is driven by the stack effect. The implication of ignoring the stack effect in two-story houses is that in general the upstairs flows will be oversized for heating, resulting in unnecessary stratification and discomfort in the winter. This upstairs-duct oversizing should actually help reduce stratification in the summer.

In addition, it is also worth noting that the duct loss multipliers for an attic and a crawlspace are the same, which is clearly inconsistent with intuition and field experiments. The result is that cooling equipment with attic ductwork is likely to be relatively undersized as compared to cooling equipment with crawlspace ductwork.

Treatment of Duct Performance in ACCA Manual D

As noted above, the principal function of Manual D is to assure that a given duct layout delivers the appropriate air flows to each room, based upon the room-by-room loads calculated with Manual J. Thus, if the total load seen by the duct run to a given room is not correct, the size of the ductwork leading to that zone will not be correct, resulting in poorly designed system (i.e., one that does not provide uniform heating or cooling, and which is difficult or impossible to balance).

There is however a disconnect within Manual D. Namely, Manual D contains an entire, fairly complete section on duct-system energy efficiency, however this section is not connected to the load calculation procedures used to size the equipment and ductwork.

Treatment of Duct Performance in ACCA Manual T

As noted above, Manual T focuses on the room-air motion aspects of air distribution systems. The way that this relates to duct performance and quality HVAC installations is through the performance of the diffusers. In particular, if a diffuser is designed to provide a given throw at a specific air flow rate, that throw will be reduced (potentially significantly) by supply-duct leakage or by flow restrictions within the ductwork (e.g., flexduct that is not fully extended, that is bent at hangers, or that is bent at too sharp of a radius).

Recommended Strategy for California

Based upon the discussion above, a two-phase strategy for improving the quality of HVAC installations is recommended. The first phase of the strategy simply addresses the issue of duct leakage, focusing on the interaction between duct leakage and equipment sizing with Manual J and Manual S. The second phase addresses the quality of the design, focusing on a methodology for accurately laying out and sizing ductwork so as to provide better occupant comfort.

The essence of the Phase-I strategy is to develop a modification to Manual J duct loss/gain multipliers that takes into account duct leakage losses, and to combine this with an appropriate training course designed to help contractors take some of the oversizing trends out of their Manual-J calculations.

The essence of the Phase-II strategy is to address the duct-design problems in the combination of Manual J and Manual D. This can be accomplished by inserting an overall duct-loss calculation procedure for each register in the house into the process. This may require some iteration between the duct-sizing procedure and the duct-loss calculation procedure, however one or two iterations will most likely be adequate, and the final design will not only provide better comfort, but should ultimately result in better energy efficiency. This overall duct-loss calculation procedure should most-likely be based on the simplified procedure developed by Palmiter (1995) that is likely to be adopted into the proposed ASHRAE Standard 152P. This procedure should be used separately for heating and cooling operation.

ATTACHMENT C

DETAILED RESULTS OF COST/BENEFIT ANALYSIS

A parametric analysis of energy-efficiency features was performed using MICROPAS4. The home used for this analysis was the California Energy Commission (CEC) typical home used for energy standards analysis. The home has 1761 square foot conditioned area and different glazing percentage (of conditioned floor area) based on Title 24 package requirements for each climate zone. In Climate Zones 3, 4, 6-10 the home has 20% glazing, and in Climate Zones 1, 2, 5, 11-16 it has 16% glazing. This file is available from both the CEC and Enercomp, the distributor of MICROPAS4.

The base-case home had Title 24 package features for each climate zone and a duct efficiency of 75%. Each feature was individually increased above these minimums to determine a difference in energy budget. The sealed duct case (R-4.2 'TIGHT') had a duct efficiency of 84%.

	CLIMATE ZONE 3

RUN DESCRIPTION	ENERGY BUDGET (kBtu/sf-yr)	FEATURE IMPACT (kBtu/sf-yr)	COST ($)	COST EFFECTIVENESS (kBtu/$100)
BASE CASE FEATURES	24.00	n/a	n/a	n/a
R-38 CEILING	23.80	0.20	$131	0.15
R-49 CEILING	23.48	0.52	$323	0.16
R-15 WALL	23.62	0.38	$190	0.20
R-19 WALL	22.69	1.31	$607	0.22
'R-21' WALL	22.37	1.63	$811	0.20
'R-24' WALL	22.02	1.98	$906	0.22
'R-25' WALL	21.79	2.21	$962	0.23
'R-25' WALL#2	21.84	2.16	$1,000	0.22
'R-26' WALL	21.63	2.37	$1,057	0.22
R-30 FLOOREXT	23.96	0.04	$9	0.44
R-5 SLAB (24")	23.01	0.99	$497	0.20
R-10 SLAB (24")	22.58	1.42	$568	0.25
ALTB (0.65)	23.13	0.87	$504	0.17
WOOD (0.55)	22.43	1.57	$2,098	0.07
VINYL (0.45)	21.36	2.64	$588	0.45
LOW-E (U=.65)	23.28	0.72	$420	0.17
LOW-SC	25.30	-1.30	$534	-0.24
LOW-E & LOW-SC	24.66	-0.66	$954	-0.07
HEAT-MIRROR 66	24.94	-0.94	$1,526	-0.06
BRONZE or GREY	24.56	-0.56	$324	-0.17
R.SHADES @ BACK	23.90	0.10	$116	0.09
M.BLINDS @ BACK	23.93	0.07	$170	0.04
R.SHADES @ ALL	23.37	0.63	$324	0.19
2' OVERHANG	23.77	0.23	$385	0.06
20% EXP.SLAB	23.74	0.26	$474	0.05
RADIANT BARRIER	23.81	0.19	$167	0.11
80% AFUE	23.76	0.24	$50	0.48
90% AFUE	22.75	1.25	$550	0.23
11.0 SEER	23.81	0.19	$155	0.12
12.0 SEER	23.66	0.34	$300	0.11
13.0 SEER	23.53	0.47	$475	0.10
15.0 SEER	23.32	0.68	$1,100	0.06
HYDRONIC #1	24.28	-0.28	$25	-1.12
HYDRONIC #2	23.79	0.21	$175	0.12
R-6.3 DUCTS	23.74	0.26	$113	0.23
R-11 DUCTS	23.56	0.44	$312	0.14
R-4.2 'TIGHT'	21.00	3.00	$384	0.78
EF=0.62	23.19	0.81	$150	0.54
EF=0.65	22.66	1.34	$350	0.38
EF=0.62 w/R12	22.06	1.94	$165	1.18
PIPE INSUL.	23.33	0.67	$95	0.71
	CLIMATE ZONE 10			

RUN DESCRIPTION	ENERGY BUDGET (kBtu/sf-yr)	FEATURE IMPACT (kBtu/sf-yr)	COST ($)	COST EFFECTIVENESS (kBtu/$100)
BASE CASE FEATURES	37.12	n/a	n/a	n/a
R-38 CEILING	36.65	0.47	$131	0.36
R-49 CEILING	36.15	0.97	$323	0.30
R-15 WALL	36.52	0.60	$190	0.32
R-19 WALL	35.18	1.94	$607	0.32
'R-21' WALL	34.68	2.44	$811	0.30
'R-24' WALL	34.14	2.98	$906	0.33
'R-25' WALL	33.79	3.33	$962	0.35
'R-25' WALL#2	33.87	3.25	$1,000	0.32
'R-26' WALL	33.56	3.56	$1,057	0.34
R-30 FLOOREXT	37.09	0.03	$9	0.33
R-5 SLAB (24")	36.14	0.98	$497	0.20
R-10 SLAB (24")	35.72	1.40	$568	0.25
ALTB (0.65)	36.26	0.86	$504	0.17
WOOD (0.55)	33.60	3.52	$2,098	0.17
VINYL (0.45)	33.22	3.90	$588	0.66
LOW-E (U=.65)	35.94	1.18	$420	0.28
LOW-SC	33.96	3.16	$534	0.59
LOW-E & LOW-SC	32.30	4.82	$954	0.51
HEAT-MIRROR 66	29.61	7.51	$1,526	0.49
BRONZE or GREY	35.67	1.45	$324	0.45
R.SHADES @ BACK	34.72	2.40	$116	2.08
M.BLINDS @ BACK	35.87	1.25	$170	0.74
R.SHADES @ ALL	33.16	3.96	$324	1.22
2' OVERHANG	36.08	1.04	$385	0.27
20% EXP.SLAB	36.61	0.51	$474	0.11
RADIANT BARRIER	36.54	0.58	$167	0.35
80% AFUE	36.93	0.19	$50	0.38
90% AFUE	36.10	1.02	$550	0.19
11.0 SEER	35.58	1.54	$155	0.99
12.0 SEER	34.30	2.82	$300	0.94
13.0 SEER	33.21	3.91	$475	0.82
15.0 SEER	31.47	5.65	$1,100	0.51
HYDRONIC #1	37.35	-0.23	$25	-0.92
HYDRONIC #2	36.96	0.16	$175	0.09
R-6.3 DUCTS	36.56	0.56	$113	0.49
R-11 DUCTS	36.25	0.87	$312	0.28
R-4.2 'TIGHT'	30.96	6.16	$384	1.60
EF=0.62	36.31	0.81	$150	0.54
EF=0.65	35.78	1.34	$350	0.38
EF=0.62 w/R12	35.18	1.94	$165	1.18
PIPE INSUL.	36.45	0.67	$95	0.71

CLIMATE ZONE 12

RUN DESCRIPTION	ENERGY BUDGET (kBtu/sf-yr)	FEATURE IMPACT (kBtu/sf-yr)	COST ($)	COST EFFECTIVENES S (kBtu/$100)
BASE CASE FEATURES	41.26	n/a	n/a	n/a
R-49 CEILING	40.73	0.53	$323	0.16
'R-21' WALL	40.67	0.59	$811	0.07
'R-24' WALL	39.99	1.27	$906	0.14
'R-25' WALL	39.53	1.73	$962	0.18
'R-25' WALL#2	39.64	1.62	$1,000	0.16
'R-26' WALL	39.23	2.03	$1,057	0.19
R-30 FLOOREXT	41.21	0.05	$9	0.55
R-5 SLAB (24")	39.77	1.49	$497	0.30
R-10 SLAB (24")	39.10	2.16	$568	0.38
WOOD (0.55)	38.79	2.47	$2,098	0.12
VINYL (0.45)	37.64	3.62	$588	0.62
LOW-E (U=.55)	39.81	1.45	$420	0.35
LOW-SC	39.61	1.65	$534	0.31
LOW-E & LOW-SC	37.68	3.58	$954	0.38
HEAT-MIRROR 66	36.57	4.69	$1,526	0.31
BRONZE or GREY	40.64	0.62	$324	0.19
R.SHADES @ BACK	38.48	2.78	$116	2.40
M.BLINDS @ BACK	39.82	1.44	$170	0.85
R.SHADES @ ALL	37.29	3.97	$324	1.22
2' OVERHANG	40.16	1.10	$385	0.29
20% EXP.SLAB	40.96	0.30	$474	0.06
RADIANT BARRIER	40.81	0.45	$167	0.27
80% AFUE	40.88	0.38	$50	0.76
90% AFUE	39.21	2.05	$550	0.37
11.0 SEER	40.07	1.19	$155	0.77
12.0 SEER	39.08	2.18	$300	0.73
13.0 SEER	38.24	3.02	$475	0.64
15.0 SEER	36.90	4.36	$1,100	0.40
HYDRONIC #1	41.72	-0.46	$25	-1.84
HYDRONIC #2	40.92	0.34	$175	0.19
R-6.3 DUCTS	40.62	0.64	$113	0.56
R-11 DUCTS	40.22	1.04	$312	0.33
R-4.2 'TIGHT'	33.97	7.29	$384	1.90
EF=0.62	40.45	0.81	$150	0.54
EF=0.65	39.92	1.34	$350	0.38
EF=0.62 w/R12	39.32	1.94	$165	1.18
PIPE INSUL.	40.59	0.67	$95	0.71